FINITE ELEMENT MODELING OF EDDY CURRENT PROBES FOR EDGE EFFECT REDUCTION

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INTRODUCTION

Eddy current methods are a widely used technique in the nondestructive inspection of aircraft structures and parts. The method consists of inducing eddy-currents in the material being tested using a probe coil. The magnetic field produced by these eddy-currents opposes that of the probe coils (Lenz's law) and the net effect is a reduced magnetic flux linking the coil. The presence of defects in the material under test disturbs the distribution of eddy-currents which in turn disturbs the net field. This change in the field is detected as a change in the impedance of the coil. The changes in coil impedance measured as the probe scans the specimen contitutes an eddy current defect signal.

In the inspection of aircraft structures, a typical geometry consists of multiple layers of aluminum along with edges and defects in one or more layers. When an inspection coil approaches an edge in the part being inspected, the eddy currents are redistributed and a large change in the impedance of the coil is detected. The edge in effect behaves like a large defect resulting in a large amplitude signal relative to the signal from a typical flaw. A defect in the vicinity of an edge is therefore completely masked by the edge signal. Consequently the design of a probe that reduces the edge effect is of interest to industry. This paper describes a new probe design based on focusing the magnetic flux of the coil, to reduce the edge effect.

Conventionally ferromagnetic shields have been used around coils to focus flux associated with coils. However these shields are effective only in air. In the application under consideration it is required to focus the flux inside the metallic test specimen. This has been accomplished using an auxiliary coil carrying a current which is different in magnitude and direction from that of the primary coil. The field distributions inside the test object can be controlled by varying the relative magnitude and direction of the currents in the coils.

It is also shown that by limiting the induced eddy currents to a smaller region the edge effect is reduced with the result that the probe is sensitive to flaws close to edges. The

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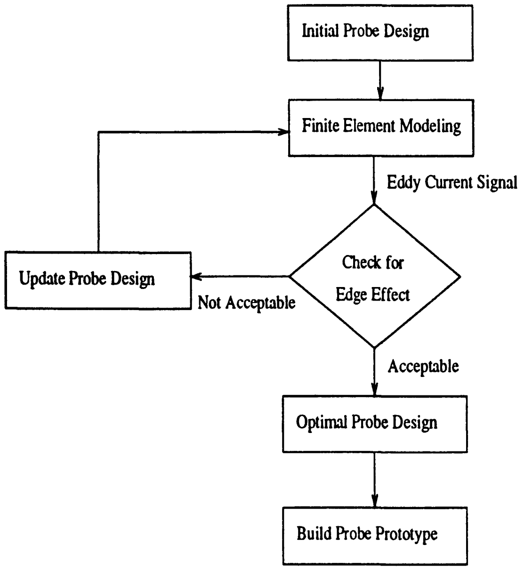

Fig. 1. Probe design approach

overall approach used in the design procedure is described in the next section. The flux focusing method and its effect on the signal due to a flaw are described in the subsequent sections. Simulation results obtained from candidate probe designs are then presented to demonstrate the feasibility of the concept.

PROBE DESIGN APPROACH

The flow chart in the Figure 1 shows the overall approach using numerical models for the optimization of probe design. An initial probe design is input to a finite element model (FEM) and the resulting eddy current signal for a defect at a critical distance from an edge is predicted. The probe is evaluated on the basis of this signal. If the defect indication is not visible in the overall edge+defect composite signal, the design parameters are modified. If the probe is able to resolve the defect contribution from that of the edge, the corresponding design parameters are used for building a prototype.

The method of finite element analysis is used to model a two dimensional (2D) axisymmetric geometry [3] of the probe coils which is described briefly below. The governing equation for the eddy current phenomenon, derived using the magnetic vector potential ($\vec{A}$) formulation result in a parabolic partial differential equation (the diffusion equation),

$$\nabla \times (\frac{1}{\mu}\nabla \times \vec{A}) = -\vec{J_s} + \sigma\frac{\partial \vec{A}}{\partial t} \qquad (1)$$

where $\vec{A}$ is the magnetic vector potential and $\vec{J_s}$ the vector source current density.

In the finite element method the region of interest is first discretized into discrete elements connected at nodal points. If the geometry to be modeled has an axis of symmetry or is infinite in one of the directions a two dimensional discretization is used. Otherwise a three dimensional (3D) discretization is required. The differential equations are solved by the formulating an energy functional set up in terms of the variables in the equation. The minimization of this function with respect to the magnectic vector potential at each node of the mesh yields the solution. This procedure results in a global matrix equation in terms of all the variables of equation (6) which can be solved for the unknown nodal magnetic vector potential ($\vec{A}$). The flux density $\vec{B}$ is then computed as $\vec{B} = \nabla \times \vec{A}$.

The impedance Z of the coils is computed as follows: Defining induced voltage in a coil of N turns

$$V = N\frac{d\phi}{dt}$$

where ϕ is the flux linking with the coil. In the case of steady state excitation we have

$$V = -j\omega N\phi$$

Using an excitation current of I amperes, the impedance of the coil,

$$Z = \frac{V}{I} = -\frac{j\omega N\phi}{I}.$$

The flux ϕ is computed using the vector $\vec{A}$ as,

$$\phi = \int_l \vec{A} \cdot \vec{dl}$$

where $\vec{l}$ is contour along the coil. In terms of nodal values of $\vec{A}$ the coil impedance is computed as

$$Z = -\sum_{i=1}^{M} \frac{j\omega N 2\pi r_i A_i}{I}.$$

where the summation is over the elements that form the coil (M elements), r_i and A_i are the radius and the magnetic vector potential computed for the ith element. Contours of flux associated with the coil can be plotted to show the field distribution in the region of interest.

FLUX FOCUSING METHOD

The approach used in this work for reducing edge-effect is based on the principles of flux focusing. The conventional method to focus the magnetic flux is through the use of magnetic sheilds placed around the coil. In this method most of the flux converges to the path of least reluctance through the sheild. The skin depth is much smaller at higher frequencies and hence the sheilding effect is prounced at high frequencies and becomes ineffective at lower frequencies.

An effective method to focus the primary coil flux lines within the conducting specimen can be obtained by using an auxiliary coil. An outer auxillary coil, concentric with the primary coil was considered. A schematic of the coil geometry is shown in Figure

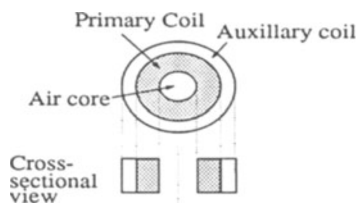

Fig. 2. Two concentric coil configuration

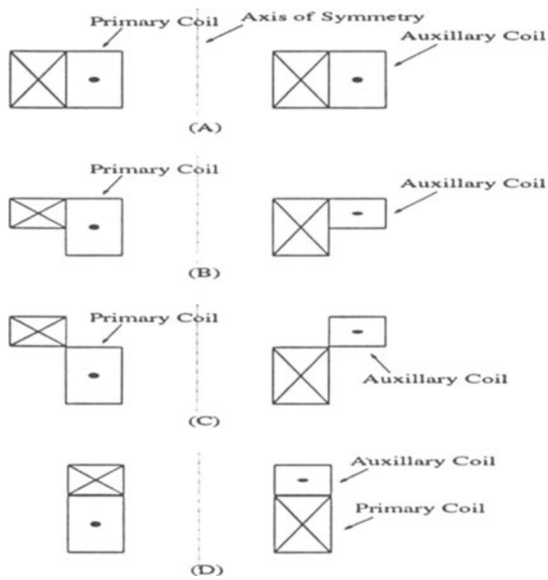

Fig. 3. Coil configurations (A,B,C,D) showing the primary and auxiliary coil cross-sections.

2 along with the cross-sectional view. The auxillary coil also carries a current and its field serves to alter the field of the primary coil. The net spatial field distribution in the test specimen can be controlled by varying the magnitude and direction of the current in the auxillary coil with respect to the primary coil.

The total field distribution in the conducting layers was studied for a variety of design parameter values. Besides magnitude and direction of currents in the coils, other probe parameters are the coil cross section areas and coil positions. The cross sectional geometry of the auxillary and primary coils are crucial for defining the net field distribution. The two concentric coil configuration has an axis of symmetry and hence the 2D finite element model can be used to obtain the magnetic flux pattern associated with the probe. Four candidate probe geometries shown in Figure 3 were modeled.

Choosing the phase difference between the currents in the 2 coils to be 180° the finite element model was executed and the corresponding flux plots obtained are presented in Figure 4. On examining the results in the Figure 4 it is seen that the most compact flux

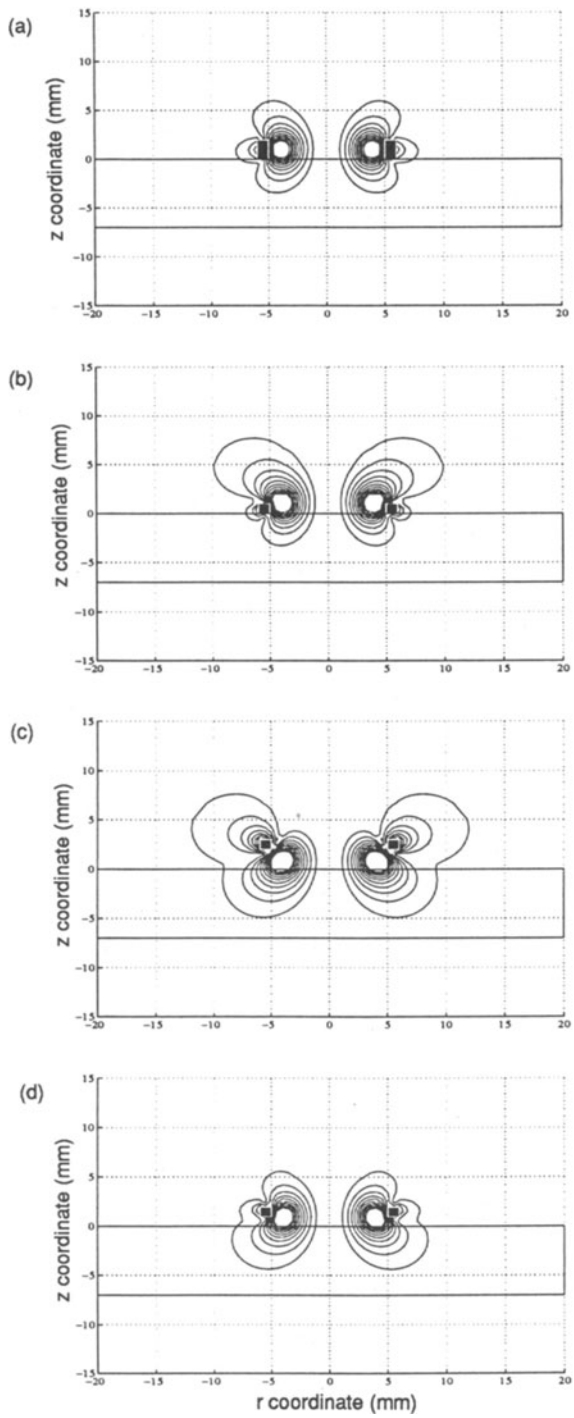

Fig. 4. Magnetic flux focusing using two concentric coils carrying opposite currents (configurations A,B,C and D)

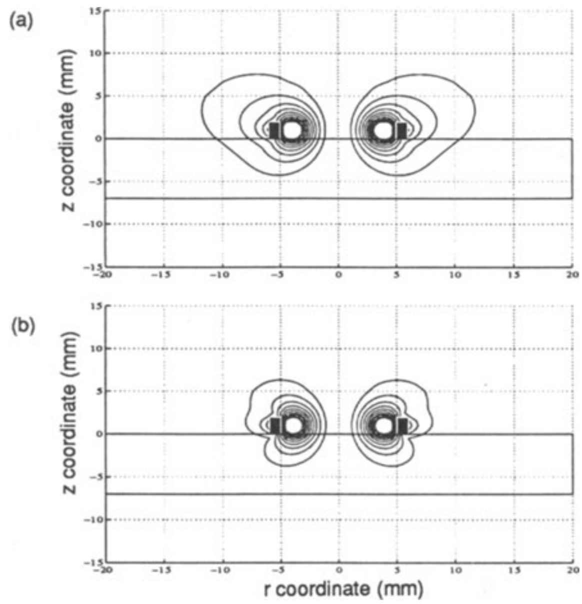

Fig. 5. Magnetic flux focusing using configuration A with variable current phase in the auxiliary coil.

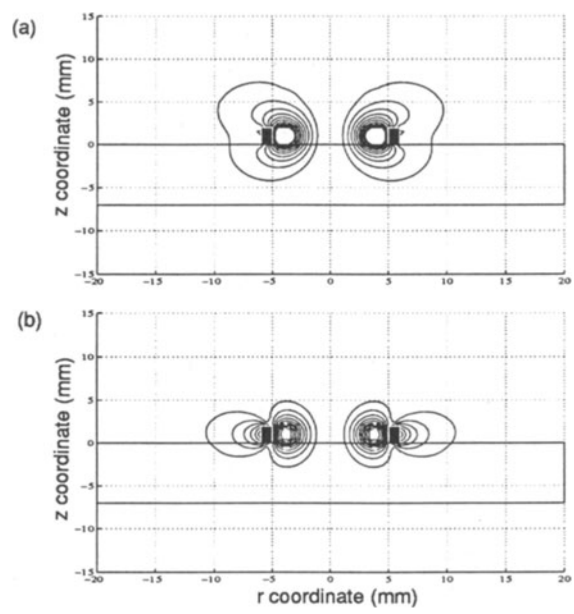

Fig. 6. Magnetic flux focusing using configuration A with variable current magnitude in the auxiliary coil.

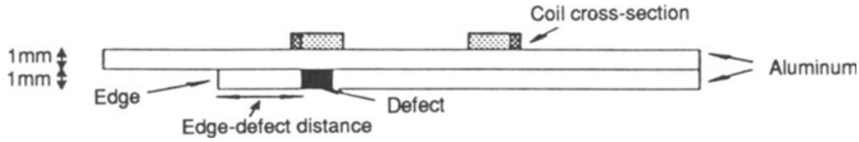

Fig. 7. Cross view of the coil geometry modeled.

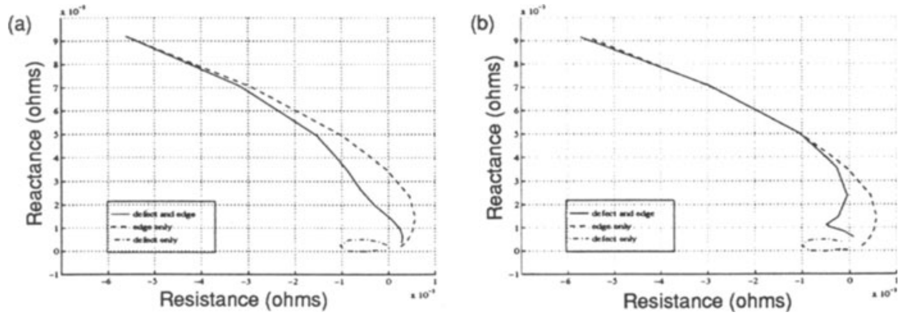

Fig. 8. Impedance plane plots for the conventional EC probe

distribution is obtained for configuration A. Correspondingly the eddy current density inside the specimen is also localized. This configuration of coils was used in further study.

Figure 5(a) and (b) show the magnetic field distribution of the coils with configuration A and a phase difference of (a) 160° and (b) 170° between the currents in the primary and auxiliary coils. The current density magnitude in both the primary and auxiliary coil is $5A/mm^2$ Keeping the primary density at $5A/mm^2$ and a fixed relative phase difference at 180°, the magnitude of the auxilliary coil current density was then varied. Figure 6(a) and (b) show the corresponding results for auxilliary current density of (a) 4 A/mm^2 and (b) 6 A/mm^2.

EDGE EFFECT REDUCTION

The probe design obtained from the previous study was used to predict the signal from a flaw in close proximity to an edge. Since this requires scanning a defect with a probe a full 3D finite element model is needed at each probe position. The change in the impedance of the primary/pickup coil is detected as a signal to indicate the presence of flaws in the sample being inspected. The geometry modeled consists of the probe on a two layered aluminum sample (each $1mm$ thick) with an edge in the second layer with a defect ($2mm \times 2mm \times 1mm$) at a specified distance from an edge as shown in Figure 7. The impedance plane plots as obtained from the numerical model for the desired probe configuration and parameters are presented in the Figures 8 and 9.

In Figure 8(a) and (b) are the impedance plane plots for the conventional eddy current probe at a edge to defect distance of (a) $3mm$ and (b) $5mm$. Figure 9(a) and (b) present the corresponding signals for the proposed probe. The impedance plane trajetories are obtained as follows. The probe signal for a scan over the sample is computed for each of the three cases: sample with defect alone (dotted and dashed loop), sample with edge

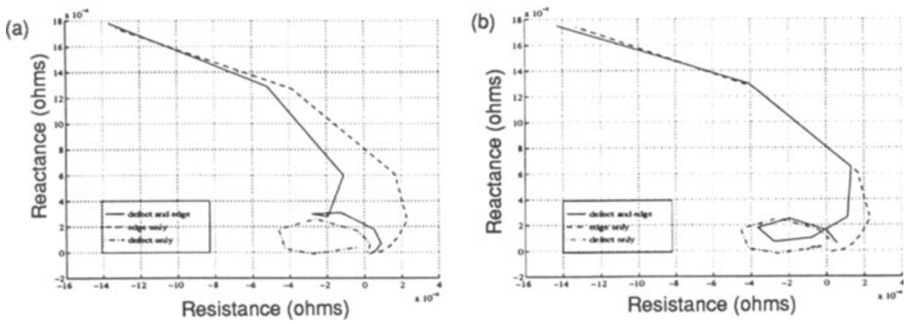

Fig. 9. Impedance plane plots for the new probe with the auxiliary coil

alone (dotted line) and, sample with both edge and defect (continuous line). The coil impedance is obtained for the probe on the aluminum plates without a defect or edge in the sample and subtracted from each of the three scan signals obtained. This produces the nulling effect so that the trajectories begin at the origin.

A comparison of the results in Figures 8 and 9 indicate that the presence of the defect at a distance of $3mm$ from the edge plotted as the continuous line graphs can be detected using the new probe. The impedance plane-plot for the conventional eddy-current probe does not indicate the presence of the defect clearly. The 3D modeling results show that it is possible to resolve a defect from an edge at a edge-defect distance of 5mm using a coil of 10mm diameter with an auxiliary coil of diameter 11mm.

CONCLUSION

A new approach for focusing flux patterns and eddy currents inside a metallic specimen has been presented. Initial results of eddy current signals obtained from the proposed probe design show significant promise in enhancing defect signals in close proximity to edges. As future work the probe design will be further optimized and a prototype of the probe will be built for experimental validation of the concept.

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